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14. ABSTRACT
The transition to a primary instability in the footprint of nonlinear internal waves of depression was investigated using spectral multidomain-based numerical simulations. The fully nonlinear internal wave fields were supplied through a highly nonlinear extended Korteweg De Vries algorithm generated by Sakai & Redekopp (2007). Results were qualitatively similar to the findings of Diamessis and Redekopp (2006). In the absence of an oncoming current, no transition was observed. Introducing a current and with a sufficiently strong wave amplitude and Reynolds number, the separated bottom boundary layer under the wave and behind its trough experienced a shear instability, accompanied by vortex shedding, powerful bottom shear-stresses and strong near-bed vertical velocities, indicating potential for resuspension. The vortex shedding was intermittent, consisting of bursts of 5-6 eject vortices alternating with calm periods. A subcritical nonlinear transition to turbulence was also identified and is currently under investigation.

15. SUBJECT TERMS
Nonlinear internal waves, continental shelf, bottom boundary layer, hydrodynamic instability, boundary layer separation, resuspension of bottom sediment.

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FINAL REPORT (3/31/201…)

Benthic Turbulence and Mixing Induced by Nonlinear Internal Waves

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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced benthic turbulence and bottom particulate resuspension.

OBJECTIVES

The specific objectives of this project were directed towards:

- Characterizing the structure and energetics of the three-dimensional turbulence and mixing in the NLIW-induced time-dependent boundary layer as a function of wave-based Reynolds number and wave amplitude. In particular, we sought to elucidate the potential for the near-bed distribution of the NLIW-induced pressure field to establish a preferred location for benthic turbulence with respect to the wave trough/peak. Critical to this objective is a robust understanding of the transition to primary instability under …lly nonlinear internal wave.
- Comparing results of implicit Large Eddy Simulation (LES) of NLIW-induced boundary layers with equivalent field observations to:
    - Flesh out the underlying fluid dynamics.
    - Provide consistency checks for the LES along with means for further refining future simulations.
    - Develop predictive tools for designing future deployments focused towards identifying signatures of energetic NLIW-induced benthic events.

APPROACH

Our approach uses implicit Large Eddy Simulation (LES) based on a spectral multidomain penalty method Navier-Stokes solver developed by the PI (Diamessis et al. 2005) for the simulation of high Reynolds number incompressible flows in vertically finite domains. The advantages of this computational tool lie in its high (spectral) accuracy, spatial adaptivity (straightforward resolution of the active regions of the flow, i.e. the bottom boundary layer and seasonal thermocline) and lack of the artificial dissipation inherent in commonly used low-order acc…y finite difference schemes

which can spuriously diffuse out critical boundary layer physics. To ensure numerical stability while preserving spectral accuracy at Reynolds number values as close as possible to oceanically relevant values, the numerical scheme is buttressed with explicit spectral filtering and a penalty method in the vertical direction.

Our problem geometry (figure 1) considers a wave fixed in a frame of reference moving with the phase speed of the NLIW through a waveguide of *uniform depth*. The wave field is introduced into the the Navier-Stokes equations in the form of forcing terms. The equations are then solved for the perturbation velocity/fields (Diamessis and Redekopp 2006) with a no-slip bottom boundary condition. If desired a barotropic tidal current is introduced, with a prescribed boundary layer profile.

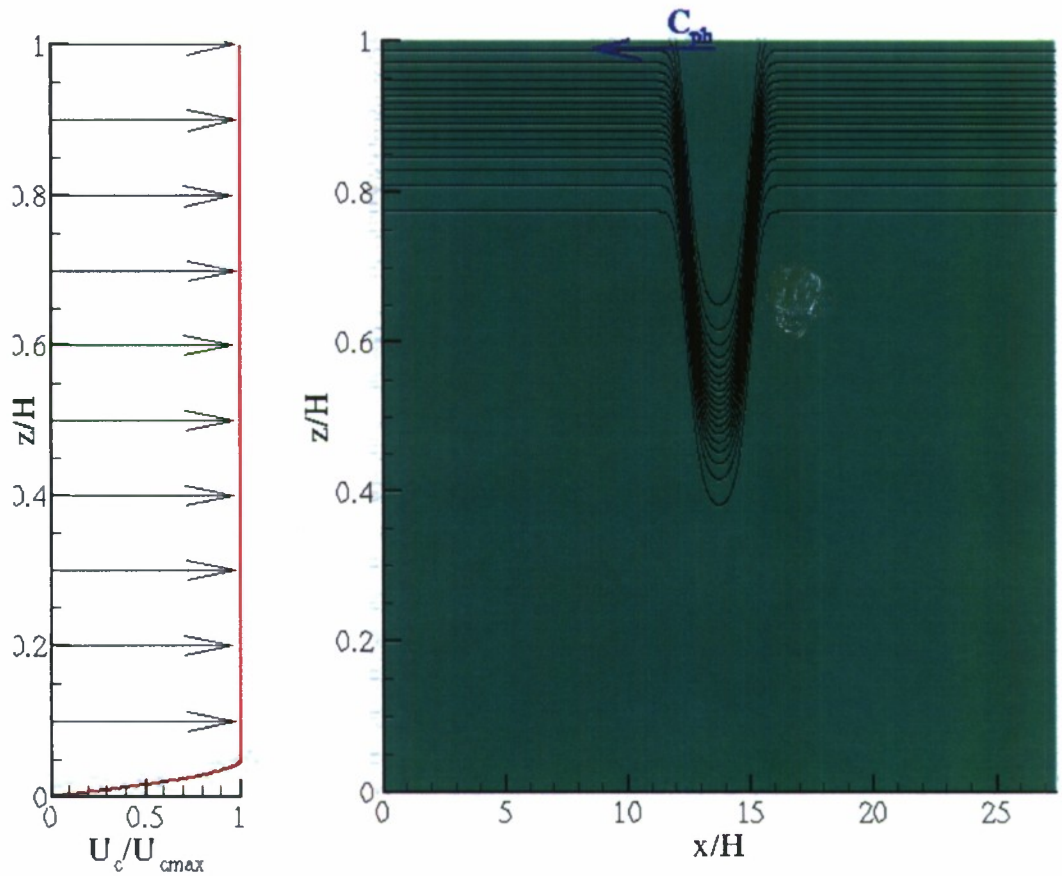


Figure 1: Problem Geometry for our simulations.
[A fully nonlinear internal wave propagates from left to right with a phase speed C_{ph} . Simulations are in a frame of reference moving with C_{ph}. If necessary, the wave propagates against an oncoming barotropic tidal current of prescribed strength with its own bottom boundary layer profile. Near-bed instabilities occur in the adverse pressure gradient region in the lee of the wave's footrpint focused in the sub-region [x/H,z/h]=[15,25]x[0,0.2].]

WORK COMPLETED

Funding of the project did not officially begin until mid-July 2007. In September 2007, a manuscript was submitted to the Journal of Physical Oceanography discussing a comparison between results obtained from 2-D numerical simulations (recast in a Eulerian reference frame) and equivalent observations in limited portions of the near-bed measurements made as part of the ONR-funded Coastal Mixing and Optics 1996 (CMO 96) field experiment. Reviews of the manuscript emphasized the need for 3-D simulations for a reliable comparison with the data from the actual oceanic boundary layer. A parallel version of our spectral multidomain penalty code, used to simulate 3-D stratified turbulent wakes (Diamessis et al., 2006), was adapted to investigate the 3-D bottom boundary layer under a NLIW of depression. However, when the code was run on the ARL MJM Linux cluster (where DOD-HPC allotted us an account), the simulations unexpectedly crashed after about 400 timesteps of run time. With minimal help from ARL technical support, 6 months were spent to identify the cause of this problem. Note that the particular parallel code has run without a problem at three other large-scale clusters (SDSC, USC and ARSC). The cause of the problem turned out to be the particular implementation of MPI on the MJM cluster and the software drivers behind the myrinet processor interconnect switches. We were allotted a new account at ARSC's midnight cluster in spring 2009. However, due to the delay we were forced to withdraw the submission from J.P.O. . We will revisit 3-D simulations in the near future (please see the "Conclusions and Future Work" section of this report).

In parallel, we constructed *fully* nonlinear internal waves, based on the theoretical model of Sakai and Redekopp (2007), which were directly incorporated into our Navier-Stokes solver. These waves replaced the weakly non-linear waves with artificially enhanced amplitude that were used in the original study of Diamessis and Redekopp (2006). Fully nonlinear waves were computed for values of the ratio of upper to lower layer thickness, h_1/h_2 within the range [1/10,1/3]. For a given value of h_1/h_2, wave amplitudes are bound by the conjugate state limit (Lamb and Wan 1998). Significant care has been taken for the wave velocity field to transition smoothly to the free-slip condition at the top surface. The thermocline thickness was chosen to be a factor of two larger than that of the wave velocity shear layer to prevent the formation of any Kelvin-Helmholtz instabilities which can significantly alter the structure of the wave.

Preliminary 2-D simulations of the transition to near-bottom instability under NLIWs of depression with the ongoing code (which uses a Fourier discretization in the along-wave direction) were limited to a very long computational domain that contained 5 wavelengths to prevent interactions of the wave with its periodic counterpart. In this case, despite dedicating 2048 points in the along wave direction, the resulting vortices shed from the unstable NLIW-driven bottom boundary layer were so small that they were captured by only 10 grid-poitns in the x-direction.

At least 50 grid-points per vortex diameter would be required to perform any meaningful 3-D L.E.S., so we decided to postpone any such effort until the availability of a more flexible solver. Thus, we decided to focus our efforts towards extensive set of 2-D simulations to investigate the transition to instability in the bottom boundary layer under both waves of depression and elevation. Our most recent investigations focused on exploring the role of background current and thermocline depth on destabilization of the NLIW-induced boundary layer. The work was performed by a graduate student, Themistoklis Stefanakis, as part of his Masters' thesis.

During the course of this project, we initiated discussions with a number of observational oceanographers. These include Profs. Jim Moum and Jonathan Nash of the Oregon State Ocean Mixing group and Prof. Tim Stanton of N.P.S. . Both groups have a significant set of field data on NLIW-induced boundary layers from the Oregon/New Jersey and Monterey Bay shelf regions, respectively. Finally, we are in regular contact with Prof. Ren-Chieh Lien, with our current interaction being focused on comparison of measurements of NLIW-induced bottom pressure perturbations with equivalent theoretical estimates on our side.

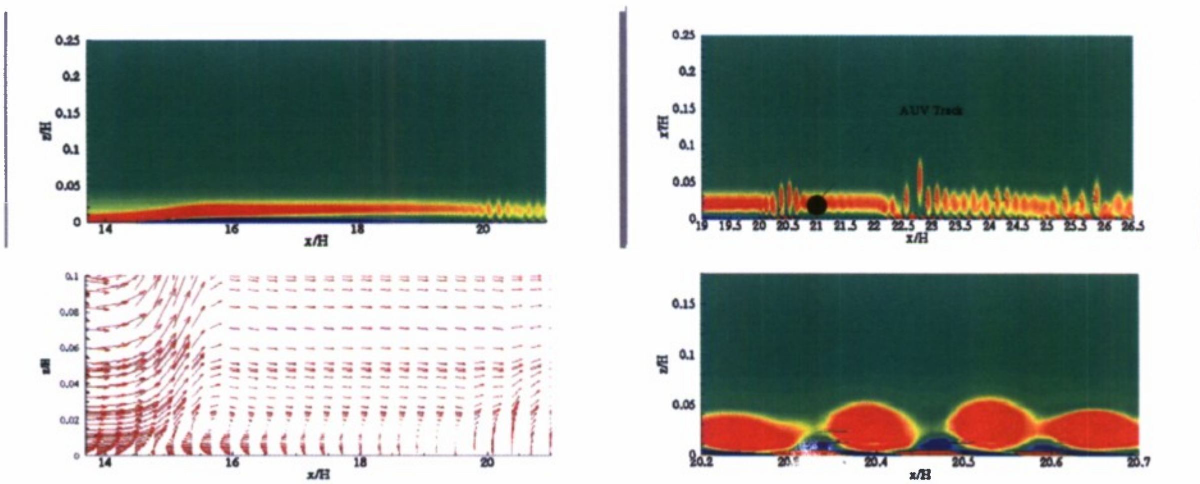
RESULTS

Our first set of simulations focused on fully nonlinear waves of elevation, in the absence of a background current. Unlike our findings in Diamessis and Redekopp (2006), we did not observe any near-bed instability. At sufficiently large wave amplitudes, trapped core formation occurred inside the wave and/or Kelvin Helmholtz instabilities along the rear of thermoclinic elevation were observed which significantly distorted the wave, in agreement with the recent laboratory study of Carr and Davies (2010). We concluded that: a) the observations of Diamessis and Redekopp (2006) for elevation waves were an artifact of the particular waveform used (weakly non-linear wave at artificially enhanced amplitude), such that they did not pertain to a fully nonlinear wave of elevation and b) in accordance with the recent findings of Stastna and Lamb (2008), near-bed instabilities occur under a fully non-linear wave of elevation occur in the presence of a background current. The bottom boundary layer needs to be sufficiently developed ahead of the wave, which is the case for the oncoming current. In the case of a wave of depression, under the appropriate conditions, the bottom boundary layer development can take place in the favorable pressure gradient region in the leading edge of the wave.

We then focused our efforts in investigating the transition to instability under fully nonlinear waves of depression. Initially, no background current was introduced. Our computational resources (serial runs on a Linux workstation) allowed us to run at a maximum wave Reynolds number of $Re=C_{ph}H/\nu$=100,000 which is comparable to the maximum value of *Re* considered in the equivalent laboratory study of Carr et al. (2008). However, unlike the lab experiments of Carr et al. (figure 3), we were unable to reproduce any near-bed shear instability in our simulations. In particular, we observed a near-bottom jet extending from the wave trough to at least one wavelength in the rear of the wave with no visible separation bubble being established. A focused separation bubble in the adverse pressure gradient of the wave is highly favorable towards near-bed shear instability and vortex shedding, the phenomenon we were looking for.

The introduction of a background current enhances the near-bed shear and forces the separated boundary layer in the rear of the wave to re-attached, enabling a more compact separation bubble which is a lot more susceptible to shear instability (see the velocity quiver plot in figure 2a). Instability waves develop inside the separation bubble and are transmitted towards the rear of the wave, partially fragmenting the rear of the bubble into coherent vortices, which are then ejected into the water column at heights of z/H~0.05 to 0.1 above the water column (figure 2b). Vortices are ejected successively in bursts of five to seven (with an approximate shedding period of tC_{ph}/H~0.15 , i.e. in 100m deep water with C_{ph}~1 m/s, every 15 seconds), with each burst followed by a quiet period where the separation bubble reconstructs itself. The cycle of vortex ejections and bubble reconstruction then repeats itself over the full course of the simulation. This cycle is a manifestation of a slower global model of "boundary layer flapping / breathing", commonly seen in 3-D simulations of boundary layer separation over airfoils (Jones et al., 2008), i.e. it is not a 2-D artifact. The ejected

vortices establish a near-bed wake propagating with the wave and have characteristic vertical velocities of
w/C_{ph}~0.05 to 0.1 and drive strong bottom shear stresses with significant spatiotemporal variability, suggesting that these events can be primary drivers of near-bottom particulate resuspension and dissipation of NLIW energy.



(a) *(b)*

Figure 2: Near-bed vorticity and velocity fields from 2-D simulations of the boundary layer induced by a NLIW of depression
[Simulations are for the two two-layer system shownin figure 1 with an oncoming current with free stream velocity equal to 40% that of NLIW phase speed. The Reynold number is equal to $Re=CH/\nu=10^5$. The has an amplitude of 0.39 the total water depth. (a): Vorticity isocontours (top) and near-bed velocity profiles (bottom --- notice, the reversed velocity profile in the separated region upstream of the wave trough) at time tC/H=7.5 after the beginning of the simulation. (b): Vorticity isocontours at time tC/H=12.1 (the bottom view shows an exploded view of the vortex packet at x/H=20)]

Simulations of 3-D separation near airfoils indicate that the vortices ejected near the source of the vortex shedding are strongly two-dimensional and develop 3-D features once they propagate at least four to five vortex diameters from their source. This observation along with the fact that the thickness, spacing and ejection height of our simulated vortices agrees well with those measured in the laboratory (figure 3) suggest that our 2-D simulations do provide a reasonable representation of the destabilization of the NLIW-induced bottom boundary layer and the near-wave structure of the associated near-bed wake. To this end, our results may guide future deployments in terms of specific measurement signatures and positioning of instrumentation along the ocean seafloor.

A number of simulations have been performed for a broad range of *Re* values, oncoming current strength and layer thickness ratio h_1/h_2. A stability boundary, which indicates the critical wave amplitude above near-which near-bed shear instability occurs as a function of *Re* is shown in figure 4 . At a given *Re*, enhanced oncoming current strength leads to a lower critical wave amplitude as the near-bed shear is intensified along with the growth-rate of the associated instability. The reduction of critical wave amplitude with a deeper thermocline (smaller value of h_1/h_2) appears to be linked to the

establishment of a more longitudinally compact separation bubble in such an environment (Stefanakis and Diamessis, 2010). Finally, critical amplitude decreases with *Re*, suggesting that at oceanically relevant Reynolds numbers, near-bed instabilities and turbulence in the form of a near-bottom wake in the wave rear and translating with the wave are likely to happen at even lower wave amplitudes, e.g. 15% .

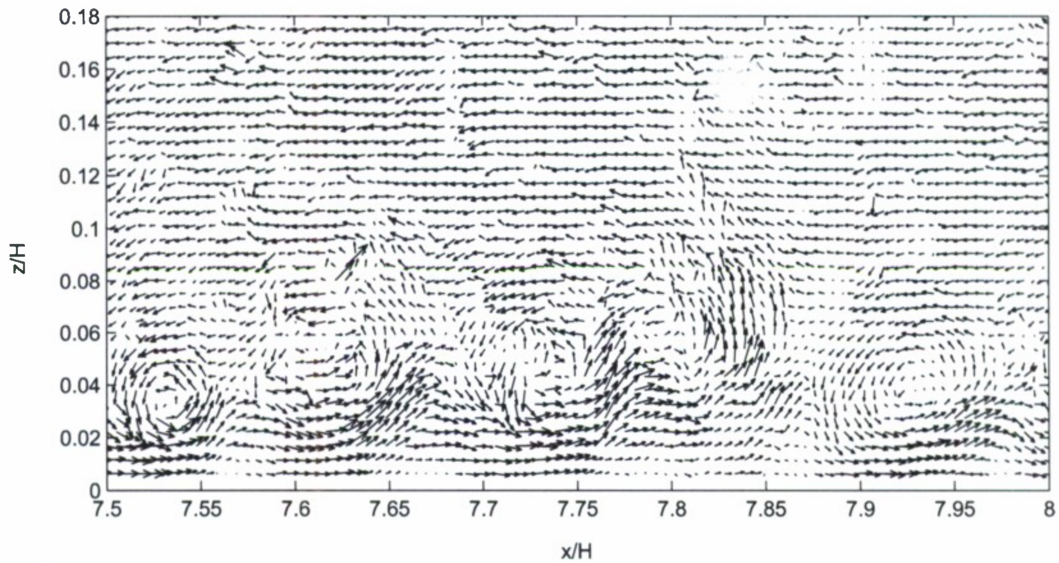


Figure 3: Velocity vectors in the lee of a NLIW of depressionf in the laboratory experiments of Carr et al. (2008) (courtesy of Dr. Magda Carr).
[The wave is propagating from left to right and its trough is centered at x/H = 13.. The specific experiment has been performed in a two-layer system with $h_1/h_2=5$ and a Reynolds number, $Re=CH/\nu=10^5$ (C and H are the NLIW phase speed and H the waveguide depth, respectively). The wave amplitude is 0.28. Notice the similarity in vortex size, spacing and height of ascent with the numerically generated (via 2-D simulations) vortices in the bottom image of figure 2b.]

Nonetheless, we remained perplexed by the fact that, at the same value of *Re*, the laboratory experiments could generate near-bed instabilities and vortex shedding at significantly lower wave amplitudes than our simulations (28% vs. 39%), without a background current and for an even deeper thermocline. Note that, in the absence of a background current, one can show that for a deeper thermocline, at a given wave amplitude, the strength of the wave-driven adverse pressure gradient and bottom boundary layer separation is weaker as is, thus, the likelihood for near-bed instabilities. We hypothesized that the emergence of near-bed instabilities in less favorable conditions in the laboratory might be a result of the wave generation process, namely through noise injected through the drawing of the gate (separating two parts of the water tank with different thermocline depth) and the more intense near-bottom pressure gradients generated as the wave forms through the steep front that results from drawing the gate.

Note that the near-bed shear instability our standard simulations reproduce is regarded as a "global instability" (Diamessis and Redekopp 2006), a key feature of which is that it develops spontaneously and is self-sustained. In other words, no external noise is required to spin-up and drive the near-bed wake described so far. However, it is likely that a subcritical transition (i.e. a transition to instability below the critical amplitudes shown in figure 4) is possible through the careful injection of a noise field. To explore this possibility and test our hypothesis regarding the laboratory observations, we

considered a case with a NLIW of subcritical amplitude for the configuration with the strongest oncoming current. The simulation was run to the point where a fully developed laminar separated boundary layer formed in the rear of the wave. The profile at the x-location of strongest flow reversal was then approximated with a hyperbolic tangent profile, for which standard linear stability analysis for parallel shear flows yielded the necessary perturbation characteristics (namely horizontal wavelength) to inject into the laminar separated boundary layer. The evolution of this test case is shown in figure 5. Upon noise injection, a train of Kelvin-Helmholtz billows formed and, like any classical convective instability, translated away from the rear of the wave. If the NLIW-induced bottom boundary layer were truly stable we would expect it to permanently relaminarize. In this case, however, the initial noise-driven instability was followed by an alternation of quiet stages with vortex packets. If no noise were introduced in this simulation no vortex shedding would have appeared. The implication is that external noise can indeed reduce the critical NLIW amplitude for instabilities to appear.

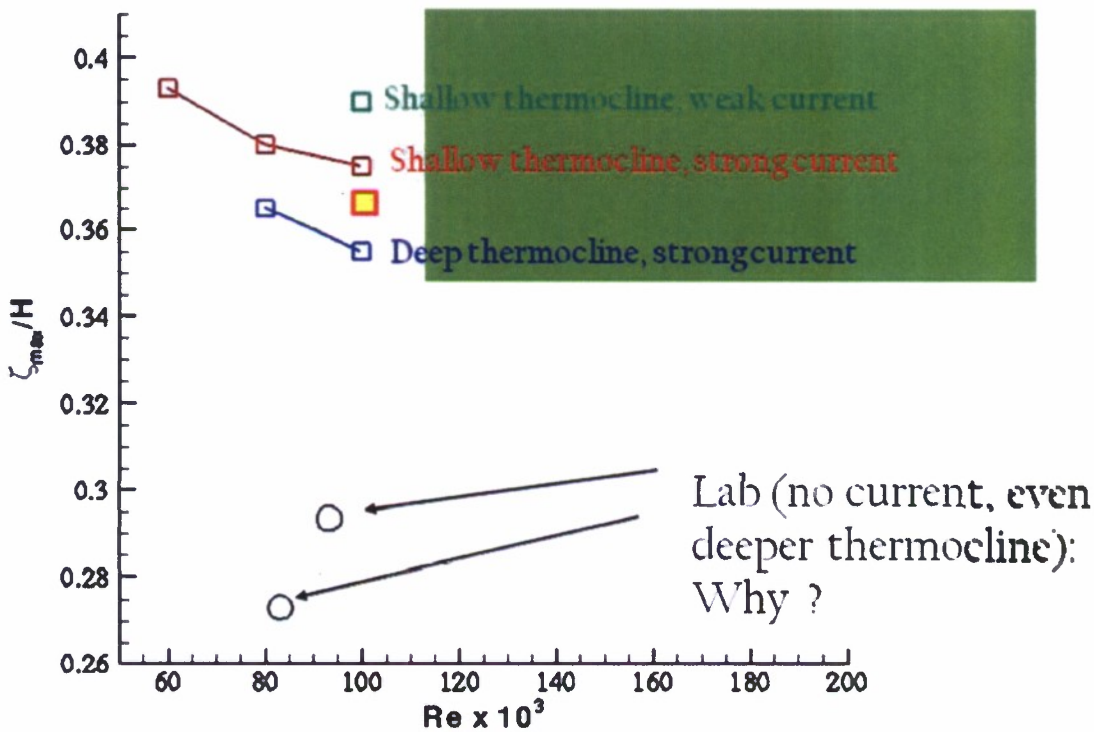


Figure 4: Stability boundary (critical wave amplitude, as measured by maximum wave-induced thermoclinic displacement normalized by total water depth, vs. wave Reynolds number). [Shown are simulations for a deep and shallow thermocline, at $h_1/h_2=1/10$ and $h_1/h_2=1/7$, respectively and for the case of weak and strong oncoming current, at 20% and 40% of the wave phase speed, respectively. At a particular Reynolds number, a deeper thermocline and stronger current induce near-bed instabilities at lower wave amplitudes. Note that the equivalent results from the laboratory study of Carr et al. (2008), denoted by circles show near-bed instabilities at even lower amplitudes, even in the absence of an oncoming current. This may be due to 3-D effects or the generation mechanism of the wave in the laboratory.]

Nevertheless, even with the injection of external noise, we were unable to reproduce near-bed instability and vortex shedding for the laboratory parameter values corresponding to figure ?? .
To this end, we speculate that for instability and transition to turbulence to happen at even lower wave amplitudes, 3-D simulations initialized with three-dimensional instabilities need to be performed. Such 3-D simulations are the objective of an O.N.R.-P.O. planning letter under preparation (See also the Conclusions/Future Work section)

The work presented here has resulted in Themistoklis Stefanakis' M.S. thesis which he will defend in mid-May. Unfortunately, Mr. Stefanakis has decided to not to stay at Cornell for a Ph.D. and will continue his graduate studies in France. The salient parts of his work have been distilled in a manuscript for *Physics of Fluids*, which we anticipate submitting in late June 2010.

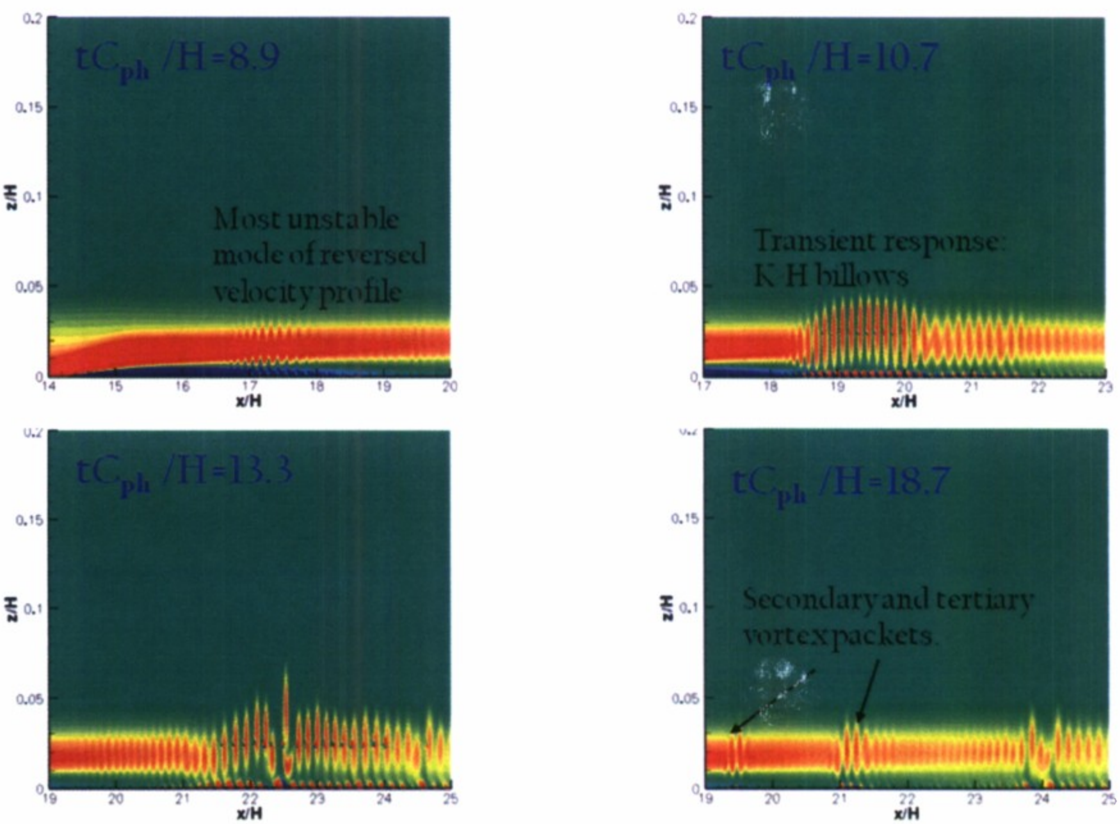


Figure 5. Subcritical transition under a NLIW propagating against a barotropic current with strenght 40% of the wave-phase speed.
[The non-dimensional wave amplitude is 37% and Re=100K. According to the stability diagram of figure 4, no near-bed instability is expected for this case. However, when an oscillatory streamwise perturbation, corresponding to the most unstable mode of the reversed velocity profile at the center of the separation bubble, a Kelvin-Helmholtz convective instability is observed. The instability then is followed by intermittent packets of vortices, presumably linked to a global instability, as a near-bed wake forms.]

IMPACT/APPLICATIONS

The benthic dissipation and mixing induced by NLIWs are linked to the terminal stage of an energetic cascade process which decides the fate of the large-scale energy input into the ocean and tides. Accurate parameterization of these mechanisms of NLIW energy is of paramount importance for the reliable performance of operational coastal ocean models. The unstable/turbulent boundary layer in the footprint of a NLIW can drive significant resuspension of biogeochemical constituents which impacts directly ocean optics and acoustics and the functionality of near-bed instrumentation. The current work will provide further insight into the physical mechanisms of the above dissipative and resuspension processes, their signatures in field observations and their implications for operational forecast modeling and remote sensing.

RELATED PROJECTS

Funded by a recently obtained NSF-Phys. Ocean. CAREER award (July 2009), a PhD student supervised by the P.I., Jorge Escobar-Vargas is currently developing a spectral *quadrilateral* multidomain penalty method solver for high Reynolds incompressible flows in doubly non-periodic domains. We currently have a full Navier-Stokes solver working in simple box domains with a direct solver for the discrete pressure Poisson equation. The latter prevents investigating flows in large domains, so we are currently focused on developing an efficiently preconditioned iterative solver. Completion of this effort and implementation of variable bottom bathymetry and code parallelization are expected by end of summer 2010. As proposed in the P.I.'s NSF CAREER award, availability of such a solver will enable the investigation of the shoaling of NLIWs over gentle slopes (i.e. propagation over *variable depth*), with a focus on the formation of trapped recirculation cores. Dr. Ren-Chieh Lien of A.P.L., U. Wash. will be actively involved in a comparison of his data from the South China Sea with our numerical results. The P.I. is also co-advising a graduate student of Prof. Leon Boegman in Queens U., Canada, in using MIT-G.C.M. to perform fully non-hydrostatic field scale simulatoins of the internal wave field in Cayuga Lake. Finally, the P.I. is serving as a co-P.I. with Prof. Phil Liu (Civil and Env. Eng., Cornell) in a recently-funded N.S.F.-CBET project which uses the P.I.'s spectral multidomain code to examine the unstable boundary layer under different types of surface waves.

CONCLUSIONS/FUTURE WORK

We have established a firmer understanding of the transition to a primary vortex shedding instability of the laminar bottom boundary layer under fully nonlinear internal waves of depression. For both NLIWs of depression and elevation, destabilization of the wave-induced boundary layer is enhanced in the presence of an oncoming background barotropic current. A near-bottom vortex wake develops in the rear of a NLIW of depression, accompanied by strong near-bottom shear stresses and vertical velocities that might be capable of driving significant near-bottom particulate resuspension. The vortex wake has a strongly intermittent character associated with a slow-timescale global mode of the shear instability of the separation bubble in the near-bottom adverse pressure gradient. These intermittent bursts of ejected vortices bear implications for preferential scourring of the ocean bottom (and the intermittent powerful sandwaves in the South China Sea, observed in echosounder measurements along the propagation path of NLIWs) and the efficient positioning of near-bed instrumentation in the field.

It is clear that the next step is to examine the structure and dynamics of the **three-dimensional** NLIW-driven bottom boundary layer. To optimally use resolution such a simulation would take place in a domain focused in the adverse pressure gradient in the rear of a NLIW of depression, equipped with appropriate inflow conditions set by the NLIW velocity field. Such a simulation will be possible with our new solver by the end of summer 2010. We intend to first examine the transition to turbulence of a laminar boundary layer developing under the wave. We will then introduce an incoming turbulent boundary layer, a proxy for the tidally-driven boundary layer on the continental shelf. In both configurations, use of a Lagrangian particle tracking algorithm, will enable the investigation of the formation of thin nepheloid layers at some height above the bed. Finally, we will focus on a comparison with field data, namely: a) n 3-D velocity profiles over 1m range above the bed measured by a 1cm resolution bistatic coherent Doppler profiler (BCDVSP) by Prof. Stanton's group in Monterey Bay and b) Vertical profiles from successive vertical microstructure casts through NLIWand timeseries from ADV's in the NLIW path deployed in the Oregon and New Jersey shelves by Prof. Moum's group.

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Diamessis, P.J., Lin, Y.C. and Domaradzki, J.A. 2008 Effective numerical viscosity in spectral multidomain penalty method-based simulations of localized turbulence. ***J. Comp. Phys.***, 227, 8145-8164.

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THESIS SUPERVISED

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To Whom It May Concern:

Please find attached my final report for the O.N.R.-Physical Oceanography-funded project titled "Benthic Turbulence and Mixing Induced by Nonlinear Internal Waves" (Award Number: N00014-07-1-0957). I apologize for the 3-week delay in sending this out but I got sidetracked by unusually high traveling and a heavy teaching load. Please let me know if you would like any additional information from me.

Sincerely,

Peter Diamessis